Improvement of magnetic properties for long YGdBCO coated conductors using TFA-MOD process

Kazunari Kimura\textsuperscript{a*}, Ryusuke Hironaga\textsuperscript{a}, Tsutomu Koizumi\textsuperscript{a}, Tatsunori Nakamura\textsuperscript{a}, Tatsuhsia Nakanishi\textsuperscript{a}, Nobuo Aoki\textsuperscript{a}, Takayo Hasegawa\textsuperscript{a}, Yasuo Takahashi\textsuperscript{b}, Masateru Yoshizumi\textsuperscript{b}, Teruo Izumi\textsuperscript{b}, Yuh Shiohara\textsuperscript{b}

\textsuperscript{a}SWCC Showa cable systems co., ltd, 4-1-1 Minami-Hashimoto, Chuo, Sagamihara, Kanagawa, 252-0253 Japan
\textsuperscript{b}Superconductivity Research Laboratory, ISTEC, 1-10-13, Shinonome, Koto, Tokyo 135-0062, Japan

Abstract

Y_xGd_{1-x}Ba_2Cu_3O_y (YGdBCO) coated conductors (CCs) containing artificial pinning centers (APCs) were fabricated by the trifluoroacetate-metalorganic deposition (TFA-MOD) method using a batch heat-treatment process, which have been industrially applied to fabricate long superconducting tapes which have high critical current (I_c) have been successfully manufactured. From the viewpoint of applications, the characteristics in magnetic fields become further important and one solution has been showed by Miura et al. [1,2] as introduction of APCs such as BaZrO_3 (BZO). We applied their technique to our CCs fabrication process. The heat-treatment conditions, specifically total gas pressure, oxygen concentration and crystallization temperature, were optimized for the batch heat-treatment process. A 40 m-long YGdBCO CC in which APCs are introduced was fabricated, and it has I_c value of 320 A/cm-width (critical current density (J_c) value of 2.2 MA/cm^2) in self-field and 20 A/cm-width at 3 T in Liq. N_2.

© 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of ISS Program Committee

Keywords: TFA-MOD process; REBCO coated conductor; Artificial pinning center; Properties in magnetic field

1. Introduction

YBa_2Cu_3O_7 (YBCO) coated conductors (CCs) by using trifluoroacetate-metalorganic deposition (TFA-MOD) method have been developed as an industrially suitable process because of the inexpensive raw material and the simple manufacturing process. We applied a batch heat-treatment process for it and successfully developed long wires with high critical current density (J_c). On the other hand, YREBCO (RE: rare-earth elements) CCs wherein a part of Yttrium is replaced with RE was reported as a next generation high temperature superconductor since the J_c is more excellent than the ordinary YBCO CCs and decrease in J_c value in magnetic fields are comparatively small. Therefore, it has received attention for a wire used in applications driven in magnetic fields such as transformers, motors and Superconducting Magnetic Energy Storage (SMES). Improvement of the superconducting properties in magnetic fields becomes further important considering that applications which work in Liquid Nitrogen being developed. Miura et al. [1-2] disclosed a way of introducing artificial pinning centers (APC) into YREBCO film using TFA-MOD
method and it was remarkably effective to improve the magnetic properties thereof and to reduce the angular dependence of $I_c$ value.

In this paper, we report on the development of Y$_2$Gd$_{1-y}$Ba$_2$Cu$_{3-y}$O$_{6.5}$ (YGdBCO) CCs with APC by a batch heat-treatment process TFA-MOD method, and the superconducting properties were evaluated in magnetic field.

2. Experimental

The precursor solution was made so that metallic element composition ratio might become Y:Gd:Ba:Cu = 0.77:0.23:1.5:3.0 by using trifluoroacetate (Y-, Gd-, Ba-) and naphthenic acid salt (Cu-). The solution was controlled to have a total metal concentration of 1.2 mol/L. Additionally, Zirconium (Zr)-naphthenates salts which became the raw material of APC were added to be the total cationic concentration by 10 mmol/L or 20 mmol/L. For the formation of superconducting layer, two steps of heat-treatments were applied, which were low temperature (calcination step) and successive high temperature annealing (crystallization step) to form the YGdBCO phase. In the calcinations step, the precursor solution was coated over a 5 mm-wide metallic substrate which has the structure of Hastelloy™ C-276/MgO (Ion-beam assisted deposition (IBAD))/CeO$_2$ (sputtering) with the traveling speed of 8.5–17 m/h, and the tape was heated by 2°C/min up to 400°C in a humid O$_2$ atmosphere. The above-mentioned process had been repeated 10–12 times to form the precursor tape having ≤1.5 μm thick superconducting layer. In the crystallization step, the furnace was heated so that the highest treatment temperature might become 740–780°C. Moreover, the parameters such as maximum temperature, total gas pressure, and oxygen partial pressure, etc. were adjusted to optimize the conditions in this process. Afterwards, the Ag stabilizing layer was formed, and post-annealing was done in the oxygen atmosphere.

It checked by XRD and EDX that BaZrO$_3$ particulates existed in a film as APC. The critical current ($I_c$) values were evaluated by a four terminal direct current method in liq. N$_2$, wherein the criterion $I_c$ value being the voltage standard 1 μV/cm. Moreover, with a split magnet consisted of the superconducting coils was used to measure the magnetic field dependence of $I_c$ value and angular dependence thereof in liquid nitrogen. For measuring $I_c$ value of a 40 m-long tape, we used a reel-to-reel $I_c$ measurement system. The voltage tapes were automatically set every 75 cm long and $I_c$ values were measured in Liq. N$_2$ with the criterion of 0.5 μV/cm.

3. Results and discussions

In order to understand the difference of the crystallization condition between YBCO and YGdBCO, short tapes were cut from the fabricated long length precursor tape and heat-treatment with various conditions using a small tube furnace. Fig. 1 shows the relationship between the heat-treatment temperature and the $I_c$ value when the oxygen partial pressure (PO$_2$) being 3.9 x 10$^{-4}$ atm and the internal total gas pressure of 300 torr. The $I_c$ values of YBCO (thickness 1.5μm) are shown in Fig. 1 as reference. As shown in this figure, the $I_c$ values of both YBCO and YGdBCO+APC (thickness 1.5μm) systems increased with increasing in the heat-treatment temperature and the highest $I_c$ values were obtained at 725°C and 760°C, respectively. In the case of YBCO tape, the window of the heat-treatment temperatures to obtain higher than 200 A/cm-w was about 50°C for YBCO [3] and 40°C for YGdBCO+APC. In addition, the maximum $I_c$ value of YGdBCO+APC was higher than that of YBCO in this experiment. It is indicated that substitution of Gadolinium pushes the crystallization temperature up and may change the growth rate.

Fig. 1. Relationship between the heat treatment temperature and the $I_c$ values.

Fig. 2. Influences of oxygen partial pressure and total gas pressure to X-ray diffraction peak heights of YGdBCO (006) in comparison with that of CeO$_2$ (200).
Growth of BaZrO$_3$ (BZO) particles brought the rack of Barium (Ba) in the system and crystal growth maybe relatively unstable, resulting in the suitable heat-treatment temperature range being little bit narrower. However, considering the $I_c$ values of YGdBCO+APC tapes, the Zr addition did not disturb the crystal growth so much.

Fig. 2 shows the relationship between the PO$_2$, the total gas pressure, and the x-ray diffraction peak height of YGdBCO (006) in comparison with that of CeO$_2$ (200). It shows the highest YGdBCO (006) peak was obtained when the oxygen partial pressure of -3.4 log(PO$_2$) (O$_2$ = 1000 ppm) and the total gas pressure of 300 torr at the heating temperature was fixed to be 760 °C. This optimized PO$_2$ was higher than that of YBCO. These results are consistent with Miura’s report [1,2]. In the case when the oxygen partial pressure was higher than the suitable region, peaks orientated in a-axis were observed. On the other hand, when the oxygen partial pressure became lower than the suitable region, all peak heights of YGdBCO were lowered.

Based on the above-mentioned optimized conditions, we performed a patched pseudo conductive sample test with a dummy tape using a large-scale batch furnace prior to fabrication of a long superconducting tape. Three pieces of 10 cm-long tapes (superconductivity layer 1.0 µm) set up at 25 m spacings on the heat-treatment drum and heat-treatment in the predetermined conditions. The $I_c$ values higher than 250 A/cm-width ($J_c$ value of 2.5 MA/cm$^2$) were obtained in all samples, which means that the batch furnace is applicable for the manufacturing process of the YGdBCO and uniform heat-treatment was performed in it.

Furthermore, the precursor tape which thickened the superconductivity layer 1.5 µm for the purpose of acquiring the high characteristic was fabricated. We performed the heat-treatment of the 40 m-long precursor tape in the batch furnace. The heat-treatment conditions were as follows; the heat-treatment temperature was 760°C, the total gas pressure 300 torr, the oxygen partial pressure -3.4 log(PO$_2$), the dew point 20°C. Figure 3 shows the result of the $I_c$ measurement of the superconducting tape by using reel-to-reel continuous $I_c$ evaluation device. $I_c$ values of about 320 A/cm-width were obtained in all sections, except of several sections having less than 300 A/cm-width of $I_c$. Actually, since no defect was observed on the surface of the superconducting layer at the lower $I_c$ part, lowering of $I_c$ value may be caused by a small defect of the substrate, intermediate layers or inside of a superconductivity layer.

The magnetic field dependence of the $I_c$ values of YGdBCO+APC CC and YBCO CC at 77 K are shown in Figures 4-a, and 4-b. Figure 4-a shows $I_c$-B characteristics when magnetic fields were applied
parallel to the tape surface (B // ab), and Figure 4-b shows in the case of B // c. The YGdBCO+APC CC has better $I_c$ value compared with YBCO CC in any condition of these measurements, which means that YGdBCO+APC CC has effective pinning center such as BaZrO$_3$ nanoparticles. Miura et al. reported clear TEM images of YGdBCO+APC in which BaZrO$_3$ nanoparticles were uniformly dispersed [2]. We supposed that such microstructure was also achieved in the samples manufactured by using the batch furnace. We measured the magnetic field angular dependence of $I_c$ of YGdBCO+APC CC and YBCO CC at 77 K, 1 T and 3 T. As shown in Figure 5-a and 5-b, the YGdBCO+APC CC had better $I_c$-$B$-$\theta$ characteristics compared with YBCO CC. $I_c$ values of the YGdBCO+APC CC are greater than those of the YBCO CC throughout angular range from -30 to 120$^\circ$ and has a peak when the magnetic field is applied parallel to the tape surface (angle: 0 degree). The strong peak at the angle of 0 degree is generally caused by intrinsic pinning center and stacking fault defects which are parallel to the ab-plane such as the extra CuO plane. Of special note of this result was that the $I_c$ value as high as 20 A/cm-width remains even at 3 T in the case of YGdBCO+APC CC. On the other hand, since YBCO CC has too low the $I_c$ value, it cannot be measured.

Considering a present outcome of the experiments, as for the coated conductors which contain Gd and Zr, there is no remarkable decrease in the $J_c$ value at self field, so that it can be understood that the $J_c$ value of the YGdBCO+APC being almost equal to that of YBCO when the Zr content was 10mmol/L. However, the amount of BZO nanoparticles caused by 10 mmol/L of Zr addition was effective to introduce APC, resulting in excellent magnetic properties being achieved.

Moreover, we fabricated the precursor tape of the 50m-long tape having Zr content was 20 mmol/L. The short sample was cut from the long precursor tape and heat treatment with the small furnace. The thickness of the YGdBCO layer was 1.5 $\mu$m. The characteristic in a magnetic field of this short sample was evaluated, and it compared with the result of YGdBCO+Zr10mmol/L. As a result, the characteristic in the inside of a magnetic field improved drastically, and $I_c$(minimum) showed 31 A/cm-w at the magnetic field impression which is 3T. It is expected that this result is because the magnetic flux was captured still more efficiently when increasing the amount of APC.

4. Conclusion

In conclusion, we successfully fabricated a 40m-long YGdBCO CC with APCs by using a TFA-MOD method. The heat-treatment was done by a large-scale batch furnace. The tape has constant $I_c$ value higher than 320 A/cm-width, which is corresponding to $J_c$ value of 2.1 MA/cm$^2$. Moreover, it contained APCs which work at Liquid N$_2$ temperature, and excellent magnetic properties were obtained.

However, it will be necessary to improve the $I_c$ values in the magnetic field further by changing the induction dose of APC, and/or increase in the superconducting layer thickness.

Acknowledgements

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO) as Collaborative Research and Development of Fundamental Technologies for Superconductivity Applications. Also, the author would like to thank the Japan Society for the Promotion of Science for their support.

References